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Hydrology of a zero-order Southern Piedmont watershed through 45 years of changing agricultural land use. Part 1. Monthly and seasonal rainfall-runoff relationships

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Abstract

Few studies have reported runoff from small agricultural watersheds over sufficiently long period so that the effect of different cover types on runoff can be examined. We analyzed 45-yrs of monthly and annual rainfall-runoff characteristics of a small (7.8 ha) zero-order typical Southern Piedmont watershed in southeastern United States. Agricultural land use varied as follows: 1. Row cropping (5-yrs); 2. Kudzu (*Pueraria lobata*; 5-yrs); 3. Grazed kudzu and rescuegrass (*Bromus catharticus*; 7-yrs); and 4. Grazed bermudagrass and winter annuals (*Cynodon dactylon*; 28-yrs). Land use and rainfall variability influenced runoff characteristics. Row cropping produced the largest runoff amount, percentage of the rainfall partitioned into runoff, and peak flow rates. Kudzu reduced spring runoff and almost eliminated summer runoff, as did a mixture of kudzu and rescuegrass (KR) compared to row cropping. Peak flow rates were also reduced during the kudzu and KR. Peak flow rates increased under bermudagrass but were lower than during row cropping. A simple process-based 'tanh' model modified to take the previous month's rainfall into account produced monthly rainfall and runoff correlations with coefficient of determination (R^2) of 0.74. The model was tested on independent data collected during drought. Mean monthly runoff was 1.65 times the observed runoff. Sustained hydrologic monitoring is essential to understanding long-term rainfall-runoff relationships in agricultural watersheds.

Keywords: Experimental watershed; Monthly rainfall; Monthly runoff; Rainfall-runoff modeling

1. Introduction

The National Resource Council (NRC, 2001) highlighted the need for reliable long-term hydrologic data at different locations to successfully address intensifying water scarcity and water related environmental problems across different regions. Few studies have reported runoff from small agricultural watersheds over sufficiently long period so that the effect of different cover types on runoff can be investigated. In the United States (US), the federal government established a network of geographically distributed experimental watersheds of various sizes throughout the nation in the 1930s. Through adaptation to

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evolving needs, they have proven to be resources of historic hydrologic data and knowledge. A 7.8 ha zero-order watershed known as W1, established in 1939 at the USDA-ARS J. Phil Campbell Sr. Natural Resource Conservation Center (JPC) near Watkinsville, Georgia (83°24′W, 33°54′N), in the Southern Piedmont, is part of this network.

The Southern Piedmont is a 16.5 million ha region in the southeastern US, extending in approximately 160-km wide zone east of the Appalachian Mountains from Virginia to Alabama (Radcliffe and West, 2000). It is one of the most eroded parts of the US as a result of generation of intensive row-crop agriculture, intense spring/summer rains and high soil erodibility. Agricultural land use patterns have changed through time in response to pressing environmental and economic factors (Hendrickson et al., 1963a; Trimble, 1974; Carreker et al., 1978). The need to study the rainfall-runoff characteristic of typical Southern Piedmont fields under varied cropping systems in order to develop predictive capabilities and recommendations for land management and conservation measures spurred the establishment of W1.

Our objective in this paper is to summarize 45 years of monthly rainfall characteristic from W1 along with that of monthly runoff in response to temporal variation in monthly rainfall and agricultural land use, and rate the agricultural land uses in terms of potential for runoff generation. We will also test how well the summarized data fit an existing rather simple process-based monthly rainfall-runoff model modified by including the previous month's rainfall.

2. Materials and methods

2.1. Data sources and analysis

Our first task was to compile the available monthly rainfall-runoff and agricultural land use data for W1 found scattered throughout several sources from 1940 to 1984. These included the ARS Water Data Center, Hydrology Laboratory, Beltsville, MD, annual reports at JPC, and several miscellaneous ARS annual and other publications (e.g. Carreker and Barnett, 1953; SPCRC, 1970; Burford et al., 1982). These data were then processed and summarized. We used various procedures of SAS (2004) for full statistical analysis determining monthly and seasonal rainfall and runoff differences within and across agricultural land uses and estimating rainfall-runoff model parameters.

2.2. Watershed description and history

The topography, soil, and land use characteristics of W1 are typical of many sloping fields throughout the Southern Piedmont. The watershed is pear shaped and lies at the headwaters of a first-order stream. The middle part is flatter with 3–4% slope. This is surrounded by 4–8% slope zones in a horse shoe fashion. Moderately eroded Cecil and Pacolet series (clayey, kaolinitic thermic Typic Kanhapludult; Chromi-Alumic Acrisol per FAO, 1998) occupy about 69 and 31% of the watershed, respectively. Cecil and related soils are mapped in over 50% of the Southern Piedmont (Radcliffe and West, 2000). The Pacolet soils have less thickness than those of the Cecil but the properties of the two soils are similar otherwise. Surface horizons generally are brownish-gray sandy loam to red clay loam and overlay red clayey argillic horizons. Saturated hydraulic conductivity varies from 10 cm h^{-1} or higher in the Ap horizon to 10^{-2}–10^{-3} cm h^{-1} in the lower Bt and BC horizons (Bruce et al., 1983).

A summary of agricultural land use at W1 from 1940 to 1984 is shown in Table 1. When established in 1939, W1 had residual vegetated bench terraces

Table 1
Summary of agricultural land use at W1 from 1940 to 1984

Period	Agricultural land use	
	Phase[a]	Description
1940–1944	Crop	Row cropping in a two year rotation of cotton (*Gossypium hirsutum* L.), oats (*Avena sativa* L.) and cowpeas (*Vigna unguiculata*).
1945–1949	Kudzu	Kudzu (*Pueraria lobata*) with corn (*Zea mays*) in first year.
1950–1956	KR	Kudzu mixed with rescuegrass (*Bromus catharticus*) with light controlled summer kudzu and winter rescuegrass grazing.
1957–1984	Bermuda	Bermudagrass (*Cynodon dactylon*) with winter annuals under rotational cow-calf grazing management.

[a] Phase indicates how the particular agricultural land use is referred to in this paper.

constructed several decades earlier by farmers and used for row crop farming. Terraces were removed in 1957 by spreading the spoil over the immediate area and establishment of bermudagrass started. Kudzu was planted throughout the South from 1935 to mid-1950s to reduce soil erosion and had value added use as forage (Everest et al., 1999). However, it fell out of favor as an envasive species after 1953. Winter annuals, such as ryegrass (*Lolium multiflorum* L.) were used to supplement the summer bermudagrass grazing after 1960. Grazing usually consisted of about 60–100 cows left in W1 to calve and care for their young from late fall to early spring (mid-November to early March). Any over-seeded rye was grazed along with any other vegetation including supplemental hay. Cows and calves were then moved for the watershed to recover. A smaller number of cows and bulls were moved in and out of W1 during breeding season beginning early April until the calving season to graze down recovered bermudagrass.

2.3. Rainfall-runoff measurement

Rainfall was measured with a chart-based Fergusson-type weighing and recording rain gauge. A 1.14 m (3.75 ft) high 2 to 1 concrete broad-crested V-notch weir fitted with a chart-based Friez-type Fw-1 water-level recorder was used to monitor runoff. Charts were manually processed to quantify and archive rainfall and runoff amounts. Data acquisition was discontinued after 1984. The weir was rehabilitated in August 1998 and data collection resumed with an automated system.

2.4. Runoff modeling

The complexity of the rainfall-runoff process makes many models either too data-intensive driven and/or too complex for useful application by many resource managers (Chiew et al., 1993; Beven, 1989). Chiew et al. (1993) compared six simple to complex rainfall runoff modeling approaches to simulate daily, monthly and annual flows in eight unregulated catchments. They concluded that the simpler models could provide adequate estimates of monthly and annual runoff in the wetter catchments and also noted the fact that it was much easier to use these models than the complex conceptual model.

We tested two of the simple modeling approaches presented in Chiew et al. (1993) as 'simple time-series model' (Tsykin equation) attributed to Tsykin (1985), and 'simple process model' (tanh equation) attributed to Boughton (1968) on monthly rainfall and runoff data collected at the W1 while planted in bermudagrass between 1957 and 1984. Chiew et al. (1993) list additional references on the Tsykin and tanh equations.

Tsykin (1985) points out the need to represent hydrologic processes with non-linear equations to reflect the non-linearity of the process. We were unsuccessful to fit our monthly rain-rainfall data to the Tsykin equation with the Gauss–Newton Method (SAS, 2004) because of lack of convergence. It may be that this equation is more appropriate in catchments where part of the runoff is accounted for by base flow. Its attraction, though, is because it considers current as well as previous month rainfalls—important for antecedent soil moisture considerations.

2.4.1. Tanh equation

The basic tanh equation, originally developed for use in small agricultural catchments with no provision for base flow, has the form

$$Y = X - \alpha - \beta \tanh\left(\frac{X-\alpha}{\beta}\right) \tag{1}$$

where Y and X are predicted runoff and observed rainfall, respectively, during a calendar month. Greek letters are used to indicate the estimated parameters. The parameter α represents a thresh hold rainfall value below which runoff would not occur, and β is a rate factor controlling additional rainfall losses through the hyperbolic tanh function ($\beta=0$, no additional losses and $\beta=\infty$, total loss).

We made a series of modifications to this basic equation by introducing the previous month's rainfall Z with various fitting parameters to allow adjustment to the runoff initiating parameter α and/or to the rate factor β. The modified equations are listed below.

$$Y = X - (\alpha - Z^{\gamma}) - \beta \tanh\left(\frac{X-(\alpha - Z^{\gamma})}{\beta}\right) \tag{2}$$

$$Y = X - \alpha - (\beta - \gamma Z)\tanh\left(\frac{X-\alpha}{\beta-\gamma Z}\right) \quad (3)$$

$$Y = X - (\alpha - Z^{\gamma}) - (\beta - Z^{\gamma})\tanh\left(\frac{X-(a-Z^{\gamma})}{\beta-Z^{\gamma}}\right) \quad (4)$$

$$Y = X - (\alpha - Z^{\gamma}) - (\beta - \gamma Z)\tanh\left(\frac{X-(\alpha-Z^{\gamma})}{\beta-\gamma Z}\right) \quad (5)$$

$$Y = X - (\alpha - Z^{\gamma}) - (\beta - Z^{\delta})\tanh\left(\frac{X-(\alpha-Z^{\gamma})}{\beta-Z^{\delta}}\right) \quad (6)$$

3. Results and discussion

3.1. Rainfall

The 12-months running average rainfall for Watkinsville from 1940 to 2004 are shown in Fig. 1. The first half of the crop-phase saw rainfall deficit while the second saw surplus compared to the long-term annual average. The kudzu-phase generally had above average annual rainfall. Seven years of below average annual rainfall followed the kudzu phase and led to significant rainfall deficit during the KR-phase. The most severe drought in Georgia since official records began in 1892 until the early 1980s occurred in 1954–55 (Plummer, 1983). After 1957, a long period of generally average or above average rainfall ensued and lasted through 1984. Runoff monitoring after weir rehabilitation in 1998 coincided with another sustained period of below average rainfall lasting through 2002. A check for temporal auto-correlation of the monthly rainfall using the ARIMA procedure of SAS found no autocorrelation between lags. The Chi Squared test for white noise indicated probability of 0.90 to lag 6, 0.88 to lag 12, 0.96 to lag 18 and 0.52 to lag 24.

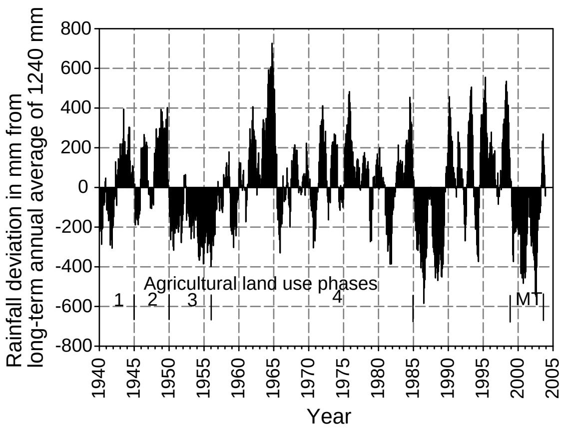

Fig. 1. Twelve months moving average rainfall for Watkinsville, Georgia, USA. The agricultural land use phases are: 1-Crop (1940–1944), 2-Kudzu (1945–1949), 3-Kudzu and Rescuegrass (1950–1957), and 4-Bermuda (1957–1984). MT indicates the period where a rainfall-runoff model was tested with independent data (Dec. 1998-Nov. 2004).

Annual rainfall accumulations in mm yr^{-1}were: 1265 for crop, 1315 for kudzu, 1044 for KR, and 1344 for bermuda phases. Mean annual rainfall for 1940–84 was 1257 mm varying from a low of 853 in 1954 to a high of 1838 mm in 1964. Mean monthly rainfall was least in October (71 mm; coefficient of variation (CV) 73%) and highest in March (149 mm; CV 45%). Seasonally, rainfall was highest in spring influenced by the March rains followed by winter, summer, and then fall. July had the highest rainfall in summer, January in winter and November in the fall. Table 2 (part I and II) shows statistical differences by seasons, pooled across agricultural land use, and by agricultural land use pooled across seasons. Table 3 shows monthly rainfall differences between agricultural land uses for each season.

3.2. Monthly runoff

3.2.1. General patterns

Agricultural land use and season were both significant in influencing runoff ($P<0.0001$ and $P=0.0002$, respectively). There was also interaction between the two ($P=0.0135$). Annual runoff accumulations (mm yr^{-1}) were 208 for crop, 127 for kudzu, 19 for KR, and 83 for bermuda. Mean annual runoff for 1940–84 was 90 mm varying from a low of 1.3 mm in 1954 to a high of 409 mm in 1964. Mean monthly runoff was least in September (0.6 mm) and highest in March (18.2 mm). Mean annual runoff percentage (percent of rainfall that became runoff) was 6.7 varying from a low of 0.2% in 1954 to a high of 22.3% in 1964. Seasonally, runoff was highest in

Table 2
Comparisons of monthly rainfall and runoff by season pooled across agricultural land uses, and by agricultural land use pooled across seasons

I. Rainfall comparison by season - pooled across agricultural land uses

Season	Rainfall mm $month^{-1}$	Statistical comparisons[a]		
		Fall	Winter	Spring
Fall	80			
Winter	116	***		
Spring	120	***	ns	
Summer	103	**	*	ns

II. Rainfall comparison by agricultural land use—pooled across seasons

Agricultural land use	Rainfall mm $month^{-1}$	Statistical comparisons[a]		
		Crop	Kudzu	KR[b]
Crop	100			
Kudzu	111	ns		
KR[b]	87	ns	**	
Bermuda	109	ns	ns	**

III. Runoff comparison by season - pooled across agricultural land uses

Season	Runoff mm $month^{-1}$	Statistical comparisons[a]		
		Fall	Winter	Spring
Fall	2.7			
Winter	9.9	**		
Spring	11.8	**	ns	
Summer	5.9	ns	ns	ns

IV. Runoff comparison by agricultural land use - pooled across seasons

Agricultural land use	Runoff mm $month^{-1}$	Statistical comparisons[a]		
		Crop	Kudzu	KR[b]
Crop	16.2			
Kudzu	11.0	ns		
KR[b]	1.5	***	**	
Bermuda	7.0	**	ns	**

[a] Statistical comparisons shown as ***, **, and * indicate significance at $\alpha=0.001$, $\alpha=0.05$, and $\alpha=0.1$, respectively, while those shown as ns indicate non-significance.
[b] The combined kudzu and rescuegrass phase.

spring followed by winter, summer, and then fall. July had the highest runoff in summer, January in winter and November in the fall. Table 2 (part III and IV) shows statistical differences by seasons pooled across agricultural land use and by agricultural land use pooled across seasons. Table 4 shows monthly runoff differences between agricultural land uses for each season.

Table 3
Comparisons of monthly rainfall by agricultural land use per season

Agricultural land use	Rainfall mm $month^{-1}$	Statistical comparisons[a]		
		Crop	Kudzu	KR[b]
Fall				
Crop	52			
Kudzu	105	**		
KR[b]	61	ns	ns	
Bermuda	85	*	ns	ns
Winter				
Crop	111			
Kudzu	134	ns		
KR[b]	100	ns	ns	
Bermuda	119	ns	ns	ns
Spring				
Crop	111			
Kudzu	123	ns		
KR[b]	101	ns	ns	
Bermuda	126	ns	ns	ns
Summer				
Crop	127			
Kudzu	83	**		
KR[b]	85	*	ns	
Bermuda	106	**	*	ns

[a] Statistical comparisons shown as ***, **, and * indicate significance at $\alpha=0.001$, $\alpha=0.05$, and $\alpha=0.1$, respectively, while those shown as ns indicate non-significance.
[b] The combined kudzu and rescuegrass phase.

3.2.2. Crop-phase

The distribution of seasonal monthly rainfall, runoff and runoff percentage for each agricultural land use phase is shown in Fig. 2. The crop-phase exposed the soil to high intensity spring and summer storms, which led to high runoff during these seasons. Winter rains saturated the soil and also produced runoff. Except for extreme events, the fall rains were generally below the threshold for initiating and sustaining runoff. Runoff was highest in summer followed by spring, winter, and fall during the crop-phase. Monthly means of runoff percentages during the crop-phase were similarly distributed: 12.2 for summer; 10.6 for spring; 10.3 for winter; and 1.9 for fall.

3.2.3. Kudzu-phase

Summer runoff was dramatically reduced, and spring runoff was reduced by almost half after kudzu became fully established (Fig. 2; Table 4). Runoff percentages were reduced from 12.2 to 0.3 in summer and 10.6 to 6.8 in spring. The summer runoff reduction was partly attributed to a reduced summer

Table 4
Comparisons of monthly runoff by agricultural land use per season

Agricultural land use	Runoff mm month^{-1}	Statistical Comparison[a]		
		Crop	Kudzu	KR[b]
Fall				
Crop	1.4			
Kudzu	11.9[c]	ns		
KR[b]	1.1	ns	*	
Bermuda	1.8	ns	*	ns
Winter				
Crop	16.8			
Kudzu	20.2	ns		
KR[b]	1.6	**	**	
Bermuda	8.9	ns	**	ns
Spring				
Crop	20.0			
Kudzu	11.7	ns		
KR[b]	3.2	**	ns	
Bermuda	12.5	ns	ns	*
Summer				
Crop	26.6			
Kudzu	0.3	***		
KR[b]	0.1	***	ns	
Bermuda	4.7	***	ns	ns

[a] Statistical comparisons shown as ***, **, and * indicate significance at $\alpha=0.001$, $\alpha=0.05$, and $\alpha=0.1$, respectively, while those shown as ns indicate non-significance.
[b] The combined kudzu and rescuegrass phase.
[c] Skewed because of one extreme value of 172.3; without this, mean=0.44 and maximum=2.79.

rainfall compared to the crop-phase (Table 3) and increased evapotranspiration from kudzu. The kudzu-phase had slightly higher runoff than the crop-phase in winter but not of statistical significance (Table 4). Mean runoff percentage was about 10.2 for both crop and kudzu phases. Fall runoff during the kudzu-phase was almost non-existent except for one extreme event (Fig. 2; Table 4), despite a 60 percent greater mean monthly rainfall compared to the crop-phase (52 versus 84 mm excluding the extreme event; Table 3). The extreme event skewed statistical inferences and interpretations. Mean runoff for fall-kudzu was 0.44 without the extreme event of 173 mm, which raised the mean to 11.92

3.2.4. Kudzu and resucegrass-phase (KR)

A combination of good ground-cover, and below normal rainfall led to almost no seasonal runoff during the KR-phase (Fig. 2; Table 2, part IV). Runoff percentage was 3 or less in fall, spring and summer, and 5 or less in winter in 90% of the events. Mean runoff percentages were 0.04, 0.54, 0.96, and 1.38 for summer, fall, winter, and spring, respectively. Statistical differences for runoff are presented in Table 4.

3.2.5. Bermuda-phase

A transition period occurred at the beginning of the bermuda-phase when terraces were removed in 1957 and bermudagrass established. The terrace removal would have contributed to the potential for increased runoff. Overall (across seasons), runoff increased compared to the KR-phase, but not the crop and kudzu phases (Table 2, part IV). This is partially attributed to increased monthly rainfall from the KR to the bermuda-phase (Table 2, part II). Summer bermuda-phase runoff was greater than summer kudzu-phase runoff, however (Table 4). Runoff once again was minimal in the fall (Table 4). Mean runoff percentages were 1.1, 1.2, 5.1, and 6.4 for fall, summer, winter, and spring, respectively. Statistical differences are presented in Table 4.

3.2.6. Runoff since 1998

Agricultural land use at W1 has continued in the bermuda-phase after 1984. Resumption of data collection after August 1998 coincided with a severe agricultural drought lasting from mid-May 1998 through mid-November 2002 in the southeastern US (Fig. 1). Historically this was one of 8 prolonged (three or more years) droughts in Georgia since 1680 (Stooksbury, 2003). The drought led to dry antecedent soil moisture conditions, which greatly reduced the potential for runoff. Nevertheless runoff was recorded in 30 of 72 months from December 1998 to November 2004. Table 5 presents summary of the runoff distribution. Runoff coefficient during this period was only 2.6%—total rainfall 6419 mm and total runoff 168 mm. On average, 7 months in a year had no runoff (58.3%). Runoff that occurred 5.6% of the time (10–50 mm) accounted for 73.5% of the total runoff volume.

3.2.7. Modeling monthly runoff

Table 6 presents parameter estimates for equations 1 and 6. About 70% of the variation in monthly runoff is explained by the variation in monthly rainfall based on the unmodified tanh equation (Eq. (1)). The coefficient of determination improved to about 75%

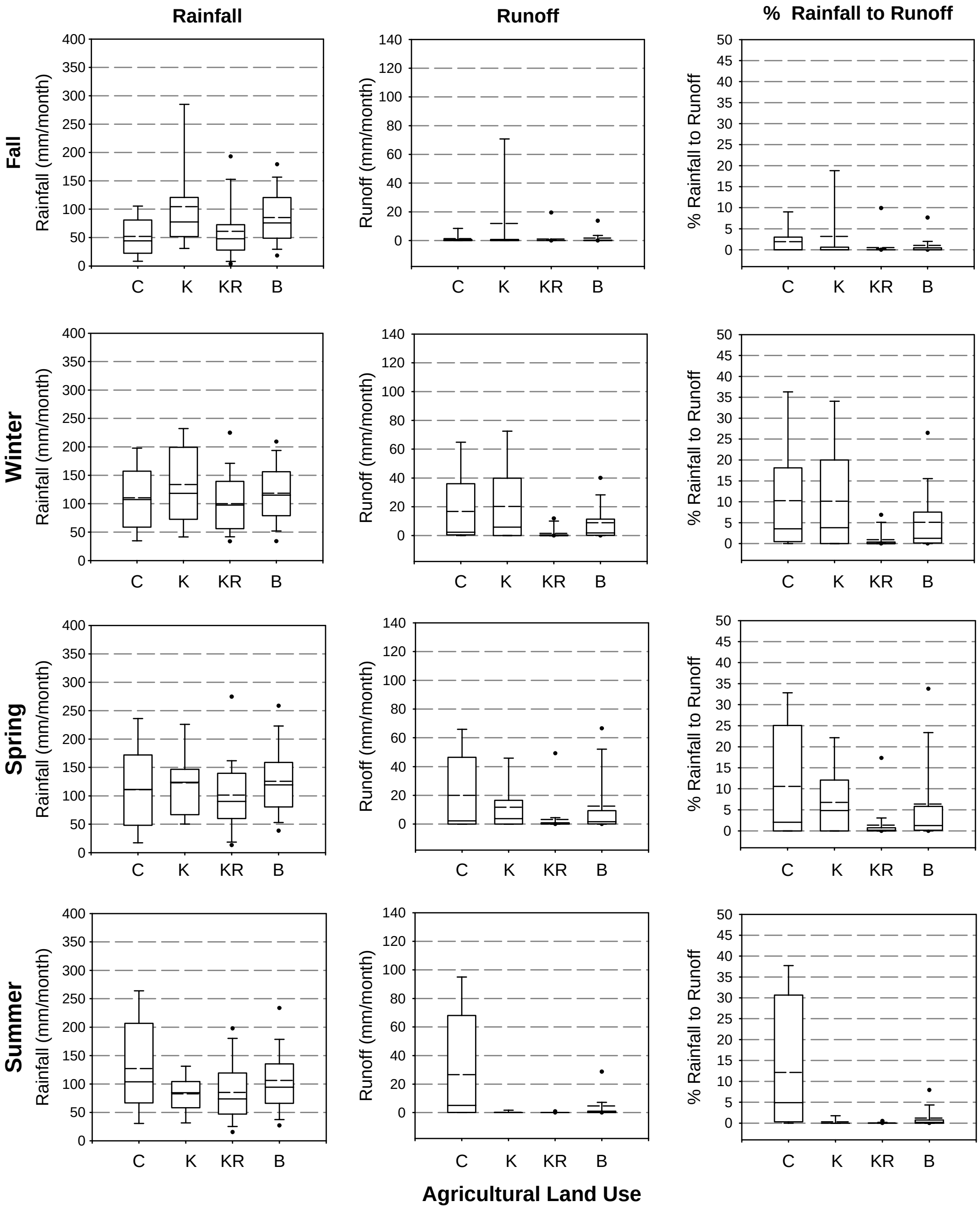

Fig. 2. Box plots showing distribution of monthly rainfall, runoff, and rainfall amount partitioned into runoff in percent, seasonally by agricultural land use, at W1 from 1940–1984. Each box shows the 25th, 50th and 75th percentiles. Means are shown as dashed lines inside boxes. Whiskers show the 10th and 90th percentiles. Outliers outside these ranges are shown as dots. Land use phases are: Crop, C; Kudzu, K; Kudzu/Rescuegrass, Kr; and Bermuda, B. Seasons are divided into three-month periods beginning in September for fall, December for winter, March for spring, and June for summer.

Table 5
Summary of runoff events by runoff classes from December 1998 to November 2004 at W1

Runoff Class (mm)	Number of months with recorded runoff								Percent of total	
	1998	1999	2000	2001	2002	2003	2004	98–04	Months	Runoff
0	1	7	8	6	7	5	8	42	58.3	0
0–0.1	–	3	–	2	2	–	–	7	9.7	0.3
0.1–0.5	–	1	2	2	–	–	–	5	6.9	0.9
0.5–1.0	–	–	1	–	–	3	–	4	5.6	1.7
1.0–2.0	–	–	–	–	–	2	–	2	2.8	1.6
2.0–5.0	–	1	2	–	–	2	–	5	6.9	9.8
5.0–10.0	–	–	–	1	–	1	1	3	4.2	12.3
10.0–20.00	–	–	–	–	–	–	1	1	1.4	11.5
20.0–30.0	–	–	–	–	–	1	–	1	1.4	17.6
30.0–40.0	–	–	–	1	–	–	–	1	1.4	20.2
40.0–50.0	–	–	–	–	–	–	1	1	1.4	24.3
Total	1	12	13	12	9	1	11	72	100	100

when the previous month's rainfall was taken into account per modified equations 2–6. Table 7 gives summary statistics for observed and predicted monthly runoff. Predicted mean monthly runoff was 2.38 times that observed with the unmodified tanh equation (Eq. (1)). This value reduced to 1.7 with the modified versions equations (3 and 6), which represents a 31% reduction in the over prediction. Monthly rainfall was between 200 and 308 mm 5 months out of the 72. In four of these, observed runoff varied from 19 to 41 mm. Eq. (6) over predicted two ($\sim$2) and under predicted the other two ($\sim$0.5). Parameters for models were established with data collected during periods of generally average or above average monthly rainfall (Fig. 1). Antecedent soil moisture conditions would have been average or wetter. The prediction was generally for a period of sustained drought where antecedent soil moisture conditions were drier than average. This may have partially contributed to over prediction generally, and especially for those few months where rainfall was relatively high.

3.3. Annual runoff and peak flow rates

Exceedance probabilities for annual rainfall, runoff, runoff percentage and peak flows are presented in Fig. 3. Annual runoff had median of 65 mm and peak of about 410 mm. The annual runoff percentage had a median of 5 and peaked at about 22. Peak annual runoff rate reached 1472 L s^{-1}, which occurred in 1945. The median annual peak flow rate was about 300 L s^{-1}. Annual peak flow rates were highest during 1940–46 with mean of 954 L s^{-1} (CV 36%). This period included the crop-phase and the first two years of kudzu when the plant had yet not achieved full ground cover. Mean annual peak flow rates plummeted to 119 L s^{-1} (CV 76%) for 1947–56 but then increased to 380 L s^{-1} (CV 81%) during 1957–84.

3.4. Monthly rainfall-runoff at other USDA-ARS watersheds

To put the W1 data in context with those from other small watersheds, a statistical summary of mean monthly rainfall-runoff between 1972 and 1979 from 10 other USDA-ARS watersheds in Oklahoma and Texas is given in Table 8, along with that of W1 for the same period. Land use for W1 was pasture while it

Table 6
Summary statistics for curve fitting of the tanh and modified tanh equation 6 with data from the bermuda phase 1957 to 1984

Statistics and parameter	Values for each equation	
	Tanh	Modified tanh
Number of iterations	3	17
Model sum of squares	79,217	84,218
Error sum of squares	33,365	28,363
Calculated R^2 (%)	70.4	74.8
Estimates		
α	16.59	50.34
β	265.10	289.50
γ		0.68
δ		0.37

Table 7
Summary statistics for observed and predicted (Eq. 1 and 6) monthly runoff (mm) from December 1998 to November 2004 at W1

Statistics	Observed values	Predicted values	
		tanh	Modified tanh
Mean	2.34	5.56	3.91
Standard error	0.87	1.58	1.30
Median	0.01	0.89	0.38
Standard deviation	7.39	13.44	11.06
Minimum	0.00	−0.01	−0.14
Maximum	40.87	79.01	69.58
Mean ratio predicted/observed	–	2.38	1.68

varied from cropping to pasture for the others. The data period varied from 36 to 72 months, not necessarily contiguously, for the watersheds other than W1. Mean annual rainfall for Riesel-TX is about 870 mm with spring contributing 270, fall 220, and winter and summer 190 mm each (Harmel et al., 2003). Chickasha-OK has a moist subhumid climate with average annual rainfall of 750 mm with spring an fall contributing the bulk (Schiebe et al., 1996). Summers are usually long, hot and relatively dry and winters short, temperate and dry. While mean monthly rainfall was higher at W1, runoff was higher at only 3 of the other watersheds. The differences could be attributed to cropping and/or evapotranspiration, and soil and topographical variability.

3.5. Controls of rainfall-runoff relationships

The scatter of the W1 monthly rainfall-runoff data (monthly runoff variance 60–80 mm in the 100–275 mm monthly rainfall range) is indicative of instability in the rainfall-runoff relationship. Since monthly rainfall is aggregate of individual rain events,

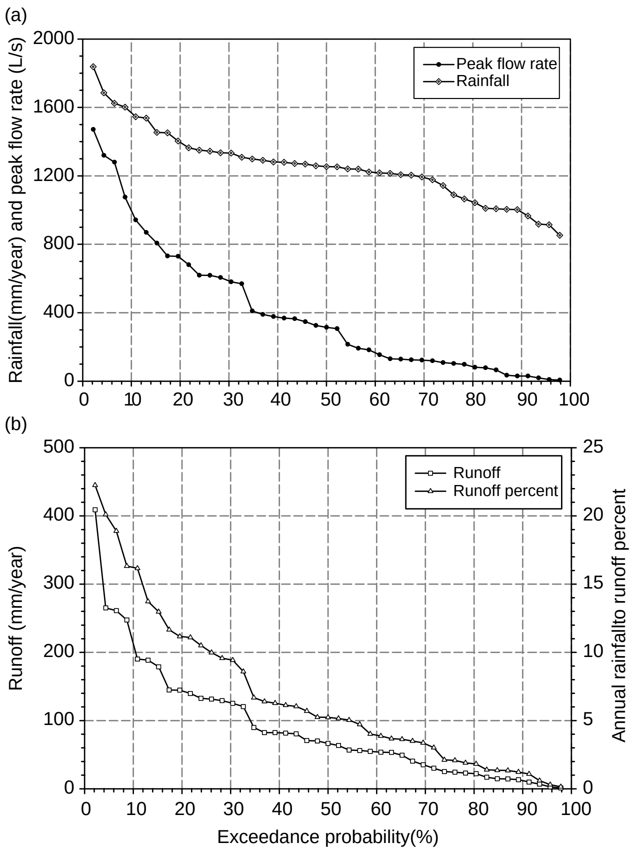

Fig. 3. Exceedance probability for annual rainfall and peak flow rate (a), and annual runoff and rainfall amount partitioned into runoff in percent (b) at W1 from 1940–1984.

Table 8
Statistical summary of monthly rainfall and runoff in mm at W1 and 10 other USDA-ARS watersheds in Oklahoma and Texas between 1972 and 1979

Parameter	Location, watershed identification and statistical values										
	Chickasha–Oklahoma[a]					Riesel–Texas[a]					JPC[b]
Watershed	C1	C7	R5	R6	R7	W6	W10	Y6	Y8	Y10	W1
Area-ha	7.2	10.7	9.6	11.0	7.8	17.1	8.0	6.6	8.4	7.5	7.8
Record #	60	60	72	72	72	96	96	96	96	96	96
Rainfall											
Mean	66.9	64.5	62.7	62.0	61.1	82.7	79.3	81.4	84.3	79.1	108.9
Median	54.5	50.5	45.8	45.7	45.3	66.5	63.8	68.2	73.7	65.7	102.4
SE	7.6	7.3	6.5	6.4	6.3	6.2	6.1	6.1	6.3	6.0	5.9
Min	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	9.1
Max	250.2	250.4	243.3	239.3	235.7	319.3	318.5	319.8	335.8	309.1	265.2
Runoff											
Mean	7.5	4.3	4.5	5.0	12.7	15.2	21.7	11.6	12.5	16.3	7.0
Median	0.1	0.0	0.1	0.0	0.0	1.5	3.2	0.1	0.5	0.1	0.5
SE	2.5	1.7	1.3	2.5	2.7	2.9	3.6	2.2	2.3	3.0	1.6
Min	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	112.5	77.0	52.5	61.3	99.8	163.7	199.7	106.9	112.9	146.4	89.3

[a] Source: Agricultural Research Service, US Department of Agriculture. Hydrologic Data for Experimental Watersheds in the United States 1972-MP 1412 (1981), 1973-MP 1420 (1982), 1974-MP 1437 (1983), 1975-MP 1441 (1985), 1976-MP 1451 (1986), 1977-MP 1454 (1987), and 1978–79 MP 1469 (1989).
[b] USDA-ARS, Watkinsville, Georgia.

ultimately the variability of those individual events influences monthly runoff patterns. At a coarse scale rainfall can be partitioned into evapotranspiration, infiltration and runoff. In our area, mean monthly potential evapotranspiration in mm d^{-1} is about 1.6 from November to February, 2.7 for March and October, 3.5 for April and September, and about 4.6 from May to August. The spring and summer rains in our region tend to be associated with thunderstorms and are intense with elevated potential to cause runoff as infiltration capacity of the soil is exceeded. The higher monthly rainfalls usually occur in spring and summer. Rainfall in winter lasts longer, and is less intense with potential to saturate the soil with any excess becoming runoff. Fall rainfall is generally inadequate to initiate and sustain significant runoff except when extreme events occur. Drought during any season reduces potential for any runoff by reducing rainfall input and drying the soil.

The analysis showed the potential for high runoff percentage from row cropping compared the grass and legume-based agricultural land use. Hendrickson et al. (1963b) similarly found that average annual runoff was 22% of annual rainfall on runoff research done from 1940 to 1954 on 6.32 m (20.74 ft) by 21.34 m (70 ft) long plots on 7% slope in continuous cotton located in close proximity to W1. Average runoff percentages equivalent to the crop, kudzu, and the first 5 years of the KR-phase of W1 were 22.7, 21.3, and 21.8, respectively. There was no runoff reduction from these cotton plots when W1 was in kudzu and KR-phases. While there are scale differences between these plots and W1, it is reasonable to conclude that runoff would not have been significantly reduced as it did during the kudzu and kudzu-resucegrass phases if W1 had remained in cropping. Conventional single-crop row cropping left the field in fallow from late fall through the winter. Then in spring soil with little cover was exposed to high-energy rainfall.

The dramatic reduction of summer runoff from cropping to kudzu could be partially attributed to greater canopy cover under and higher evapotranspiration (ET) from kudzu. The literature indicates kudzu as being an aggressive and successful competitor with large trifoliolate leaves and a perennial rhizomatus root system extending 2.5 m depth. It covers the ground with dense canopy which may reach a leaf area index of over 7 (Forseth and Teramura, 1986). A high light-saturated rate of photosynthesis on a leaf area basis and a biomass allocation that emphasizes photosynthetic over support tissues gives kudzu large advantage in biomass productivity over the competition (Forseth and Teramura, 1987). At peak growth, kudzu ET of over 10 mm d^{-1} has been reported by Forseth and Teramura (1986, 1987). Ground cover reduces crusting and increases infiltration in Cecil soils. Kudzu has hardly any ET in winter because the above ground biomass is dead.

4. Conclusions

In Southern Piedmont, clean-tilled row cropping has clearly the potential for high runoff and consequently for land degradation. Year round ground cover offers the best protection for Southern Piedmont farmlands. This is particularly true in spring and summer seasons when ground cover can be used to absorb part of the energy of the typically high intensity rainfall and reduce potential runoff.

Given the many factors that influence runoff and the fact that monthly rainfall is made up of aggregates of individual rain events, the simple process-based tanh model modified to take previous months rainfall into account (Eq. 6), appears to give a reasonable estimate, albeit elevated by a factor of about 1.6, of the monthly rainfall at W1 under pasture. This over prediction might have been related to dry condition prevailing during the model application as opposed to during parameter estimation. It appears to be a useful tool for managers for estimation of monthly runoff, especially since monthly rainfall is one of the commonly available hydrologic data.

Historic hydrologic data are vital for making informed decisions and predictions in water resource management and planning. Results from our analysis of the 45-yr data at the monthly scale, and the additional analysis possible for this data set should prove useful for more refined modeling and investigation of other hydrologic-land use interaction issues.

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Appendix A. Acronyms

ARS	United States Department of Agriculture, Agricultural Research Service
JPC	J. Phil Campbell Sr. Natural Resource Conservation Center
NRC	National Research Council
SPCRC	Southern Piedmont Conservation Research Center
US	Untied States of America
USDA	United States Department of Agriculture

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